Voltage Profile Improvement of Distribution System using Dynamic Evolution Controller for Boost Converter in Photovoltaic System

Sheeba Jeba Malar J, Jayaraju M.

Abstract: ***The existing electrical network faces problem for control and operation, since the power flow from the PV system is inconstant and hence there will be voltage fluctuation in the AC grid. This study focuses on the analysis of PV system connected to the utility grid through boost converter whose duty cycle is generated by Dynamic Evolution Controller (DEC) that applies the control law which is a function of input voltage, output voltage and inductor current, that generates a control signal which will be applied to the boost converter in such a way that it takes the voltage to a value which will operate the PV at its maximum power. The constant DC voltage thus obtained is converted to AC by using an inverter before connecting to the grid. To check the voltage variation due to the injection of PV and the effect of DEC, load flow analysis is done on IEEE 33 bus radial distribution system by connecting it in the weaker bus. The simulation is done using MATLAB/SIMULINK and the results shows that there is considerable improvement in system voltage profile at the terminal nodes in the radial distribution system than the rest of the nodes.***

Index Terms: ***Radial distribution system, Photo Voltaic source, Dynamic Evolution Controller, Boost converter, duty cycle***

I. INTRODUCTION

Renewable energy sources like solar are found to be cost effective and if they are properly planned and controlled they can alter the power flow and improve the voltage profile. As the output voltage fluctuates due to variation in load and supply, most electronic equipment could not be connected directly and hence a DC-DC boost converter which can step up the voltage and maintain a constant output is needed. The use of closed loop voltage controllers in PV system assures that the voltage of the radial distribution feeder is maintained below the maximum voltage and the consumer terminal voltage variations are as low as possible. The selection of proper controller with faster settling time is needed to maintain the terminal voltage within limits and a quick and accurate load flow solution is essential for the analysis and the performance analysis of PV system with its controller is necessary to ensure the reliability of the grid. A linear time invariant model of the switched DC-DC power converter using feedback control method [1] gives the performance of the control schemes only for small signal assumption.

The mathematical model derived [2] shows the reduction of loss component of DC-DC converter in ZVS mode but it operates only at an optimum operating point for maximum power conversion efficiency. The capability of the boost converter in improving the output voltage using conventional PI controller for closed loop system is shown in [3], but the initial rise is very high which may affect the electronic devices used in the system. Moreover, it will affect the system stability while connected to the grid. The control scheme used in DC-DC power converter must be able to ensure that the influence due to uncertainties in the input and changes in the load resistance does not affect the voltage of the system.

The performance of Dynamic Evolution Controller (DEC) for boost converter is analyzed in [4] and [5] with a step load change which operates with no initial overshoot, but it is not tested for systems with change in input voltage like Photovoltaic systems which is intermittent in nature. Hence in this proposed system the output of PV is connected to boost converter whose gate is controlled using Dynamic Evolution Controller and the output is connected to inverter and the same is introduced in the IEEE 33 node radial test case. Load flow is done using backward forward sweep algorithm since it is superior to other methods in simplicity, flexibility and computational time [6]. The line and load data [7] and a small signal model of PV, DC/DC boost converter, DEC controller and inverter are simulated in MATLAB/SIMULINK software. The whole system is connected to 11KV distribution feeder and the system has succeeded in maintaining constant voltage for different insolation levels and improving the voltage profile at the terminal nodes than the other nodes of the radial distribution system.

II. SYSTEM MODEL

A. Solar Panel

The process of generating electric power by converting solar radiation to dc by making use of semiconductors that exhibit photovoltaic effect is called photovoltaic (PV) systems. The PV system is usually a combination of many PV modules connected in series and parallel to achieve the suitable power rating. It is modeled using the following equations.

$$I = I_{ph} - I_d - I_p$$

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$$= I_{ph} - \left(I_o\left[e^{\frac{q(V + R_s I)}{mkT}} - 1\right]\right) - I_p$$

and

$$I_p = \frac{V + IR_s}{R_p}$$

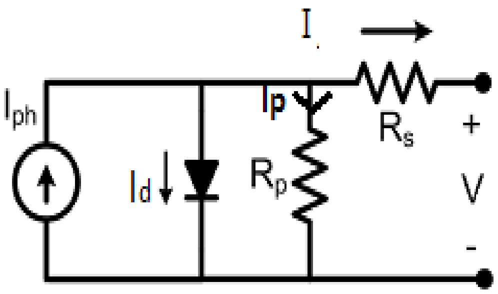

Fig. 1. Equivalent Circuit of a PV cell.

The equivalent circuit of a PV model with a photocurrent I_{ph}, a diode with current I_d, a parallel resistor R_p to express the leakage current and a series resistor R_s to describe the internal resistance to the flow of current is shown in Fig. 1.

The solar PV array used for the analysis is configured to have six series connected solar modules each having a peak voltage of 17.2V and peak current of 4.95A and two such solar arrays are connected in series to form a panel to get an output voltage of 210V with maximum power 1 KW. These parameters are used for the solar panel at standard test conditions of 1KW/m^2 at 25 ^{0}C. The specification of the PV system used for the analysis is shown in Table I.

Table I. Specification of PV System Ms Shell ULTRA SQ85-P (1000W/M^2, 25^{O}C)

Short circuit current, I_{sc}	5.45A
Open Circuit Voltage, V_{oc}	22.2V
Current at Peak Power, I_{mp}	4.95 A
Voltage at peak power, V_{mp}	17.2V
Maximum power, P_m	85W

B. DC-DC Boost Converter

The DC-DC boost converter shown in Fig.2 is used to regulate the PV array voltage to fixed dc output, which can be used to provide the required power to the load. The inductor is charged during the previous cycle of operation and the boost converter works in continuous current mode condition and at steady state. The voltage obtained from PV which is proportional to the change in current with insolation is boosted to 570 V and this is inverted to ac by using inverter. The current ripple is considered to be 10% of boost converter inductor current and the switching frequency is 10KHz.

In this proposed method, the duty cycle which is the ratio of on duration to total period is adjusted by Dynamic Evolution Controller which takes the difference between the output and the reference voltage and applies the control law to get the desired output. This boost circuit accepts an input varying from 180V to 210 V and outputs a constant voltage of 570V dc.

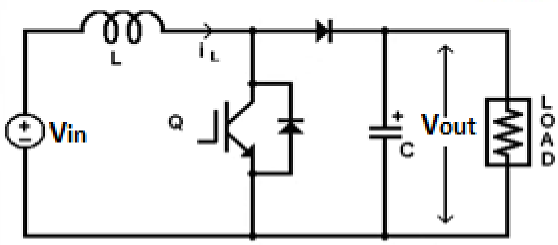

Fig.2 Boost Converter

C. Inverter

Our electric power infrastructure as well as many loads are ac and as such it is necessary to convert the dc output from photovoltaic to ac. In an inverter, the dc produced from DC/DC boost converter is inverted to ac using solid state devices such as IGBT and flips the power back and forth producing ac power. The inverter used here is a voltage source inverter where the input voltage is maintained constant and the output voltage amplitude does not depend on load but the load current depends on load impedance. The dc input voltage of inverter has to be greater than the ac peak voltage on primary side of transformer to convert dc to ac. With a minimum PV voltage of 570 V dc, the highest line-line rms voltage that can be created is 415V ac if the modulation index is taken as 0.9.

If the inverter is operated in 180^0 conduction mode, the dc voltage that is required to get the 3 phase line-line rms voltage can be calculated from the following equation [8].

$$V_{L-L}\, rms = \sqrt{\frac{2}{3}}\, V_d m_a$$

Where m_a is the modulation index. On solving we get

$$V_d \cong 570\ V$$

$$V_{L-N}\, rms = V_P = \sqrt{\frac{1}{3}}\, V_{L-L}$$

$$V_{L-N}\, rms \cong 240V$$

Hence in this work the PV is designed in such a way that it produces a constant 570 V dc from input ranging from 180V to 210 V which enables the inverter to produce 415 $V_{L-L}\, rms$. Fig. 3 shows the output obtained from the inverter which produces 240V line to neutral rms and per-unit for all the 3 phases when connected to the load. As per REC standards, a single phase system is used for smaller loads up to about 10KW and a 3 phase system for higher loads. In this case small load of 1KW is assumed and hence load flow analysis is done for a single phase system by considering only one phase into account. This per-unit voltage in phase 'a' is given as the generation from PV is shown in Fig 4.

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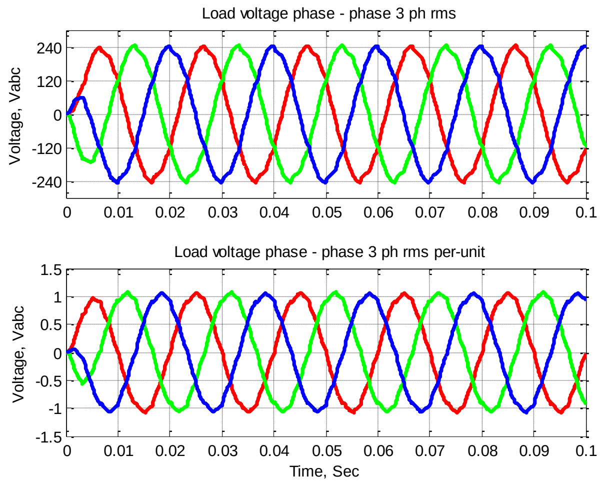

Fig. 3 Three phase rms and per unit values of Load voltage

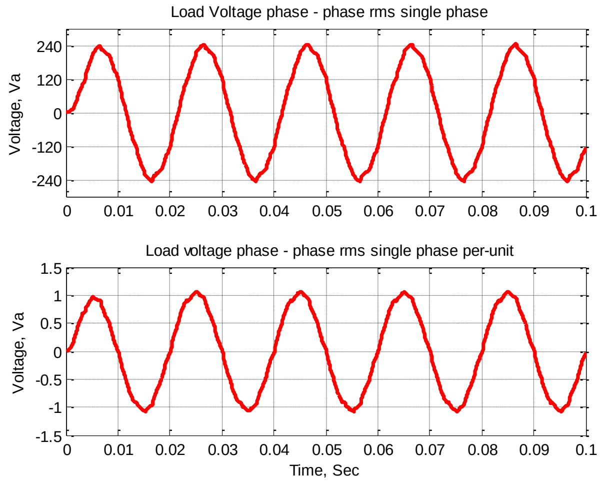

Fig. 4 Load voltage in rms and per-unit for single phase

III. SYSTEM MODEL

A. Dynamic evolution Concept

In feedback control system the actual output quantity is compared with the reference quantity and it attempts to reduce the error, whether the error is present or not. This forms the basic law of Dynamic Evolution controller (DEC) [4&5]. In a nutshell, the aim of a DEC is to make the error track a specific path so that the error decreases to zero as time increases. Fig.5 shows the path selected which is an exponential function.

The equation for exponential evolution is given as

$$A = A_0\, e^{-mt} \qquad (1)$$

A - error function
A_0 - initial value of the error function
m - rate of evolution

After taking derivative and simplifying, equation (1) becomes

$$\frac{dA}{dt} = -\, mA_0\, e^{-mt}$$

where $m > 0$

$$\frac{dA}{dt} + mA = 0 \qquad (2)$$

which is the dynamic evolution function.

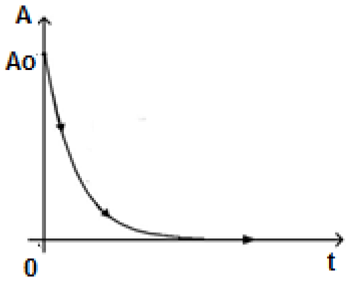

Fig.5 Exponential Path

The PWM signal used for the gate pulse is generated by comparing the error with a constant switching frequency saw tooth waveform.

B. Expression for Duty Cycle

The duty cycle equation which forces the error state to zero can be derived from the boost converter output as follows. Based on the state space average model the voltage and current dynamics of the boost DC-DC converter are given by

$$V_{in} - L\frac{diL}{dt} - V_{out}\,(1 - D) = 0 \qquad (3)$$

On rearranging (3)

$$V_{out} = V_{in} + V_{out}D - L\frac{diL}{dt} \qquad (4)$$

Inorder to apply DEC to boost converter, the state error function of error voltage is

$$A = K\, V_e \qquad (5)$$

K - Positive coefficient
V_e - Error voltage which is given by

$$V_e = V_{ref} - V_{out} \qquad (6)$$

Simplifying equation (6) we get

$$\mathrm{K}\,\frac{dVe}{dt} + (m\,K - 1)\,V_e + V_{ref} = V_{out} \qquad (7)$$

Substitute V_{out} from (7) in (4) and simplifying we get

$$D = \mathrm{K}\frac{\frac{dVe}{dt}}{V_{out}} + \frac{(m\,K - 1)\,V_e}{V_{out}} + \frac{L\frac{diL}{dt}}{V_{out}} + \frac{V_{ref} - V_{in}}{V_{out}} \qquad (8)$$

D is the control action for the converter controller which forces the state error function A to satisfy the dynamic evolution path and decrease to zero with decreased rate of 'm'. It is clear that the above equation has four parts.

The first term consists of the derivative of disturbance in the output voltage.

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The second term consists of the proportional term of the disturbance.

The third term is the derivative of the inductor current which controls the current to desired value.

The fourth term compensates for changes in the input voltage.

Properly tuning the controller parameter 'm' enables the output of the system to match with the output of the reference value, at which the error converges to zero and the maximum power is obtained.

C. Identification of Weaker bus

In load flow analysis, the sensitive node is the one which has more probability to suffer by the changes in load demands[9]. Power flow analysis is done initially and then the load is increased in steps and the voltage profile at each change and the average is taken and subtracted with the original power flow result. The voltage at the bus with more difference is considered as most sensitive node or weaker bus. Studies have shown that by adding PV at selected weaker buses of the existing utility system, the voltage profile and the stability of the system are improved [10] [11].

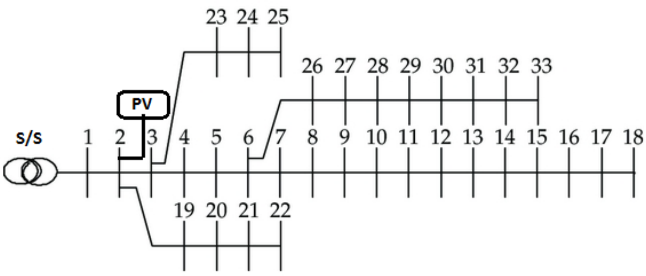

Fig.6 single line diagram of IEEE 33 bus distribution system with PV at bus 2

The whole analysis is done in an IEEE 33 bus system and it is found that when the voltage is increased by 10% the deviation is more in bus 2 which means that this bus has the highest risk of voltage instability. Hence bus 2 is ide*ntified as weaker bus and PV is connected to this bus shown in Fig. 6.*

D. Distribution Load Flow Analysis

The variation in voltage due to the injection of power generated from PV can be found using load flow analysis which determines the steady state operating conditions and checks whether the voltage profiles are within limits throughout the network. The distribution feeder is unbalanced due to unequal single phase loads and it usually operates with a radial structure and since R/X ratio of distribution lines is high, load flow methods used for transmission system is inadequate as they do not deal with radial/weak mesh distribution network and may cause conventional power flow algorithms fail to converge. A brief review of the distribution power flows is mentioned in [12] which shows the different computational methods. PV is fed at bus number 2 and backward/forward sweep method which uses Kirchhoff's current and voltage law is used for load flow in the IEEE 33 bus radial distribution system Fig 7. The forward sweep which starts from the last node and ends at the source node is a current summation method with voltage updates. Similarly, the backward sweep starts from the source node and ends at the last node is a voltage drop calculation with current updates. The evaluation is done and the change in voltage is analyzed with PV connected and PV not connected, with and without DEC.

The power injection from the integration of renewable energy based distributed generation when located close to the load centers plays an important role in system voltage support and reliability improvement. The photovoltaic source connected to the distribution network is modeled using dynamic evolution controller in such a way that it produces power at a specified terminal voltage. Hence the generation using the Photovoltaic source is modeled as a negative load with the current injected into the bus and since it supplies power to the load it can be treated as negative PQ node.

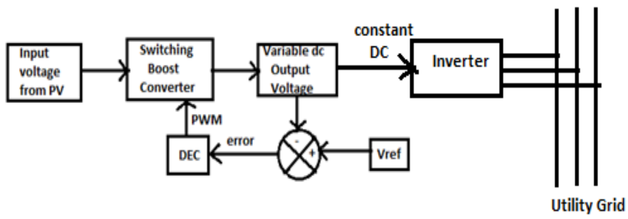

Fig. 7 Block diagram of the proposed system

The DC voltage level in this study is 570 V and the grid voltage level is 415V rms and the photovoltaic system is connected to a 11KV distribution feeder.

The nominal voltage used for per unit measurement is 11KV which is taken as the base voltage. The base power is considered to be 100MVA.

$$P_{p.u} = \frac{P_{act}}{1000\ X\ MVA_b}$$

At bus 2 the actual active power is 100KW. Hence the per-unit power at this bus becomes 100 e^{-5}. The PV output from boosted inverter is added to this bus as a negative load since it is considered to supply the load.

IV. RESULTS AND DISCUSSION

The simulation is done by varying the insolation from 880 W/m^2 to 1000 W/m^2, the corresponding change in current and the voltage proportional to this current which varies from 180V to 210V is send as input to the boost converter which boosts the value to 570V. The simulated outputs are shown in Fig. 8,9 and 10.

The effectiveness of the proposed system for voltage profile improvement is tested with the backward/forward sweep algorithm for power flow calculation in a distributed network by connecting to an IEEE 33 bus radial distribution test system under load and solar PV as the source. It is implemented using MATLAB/SIMULINK by giving special consideration to voltage profile of the network. It is assumed that the load is more than PV capacity to ensure that the system is absorption type.

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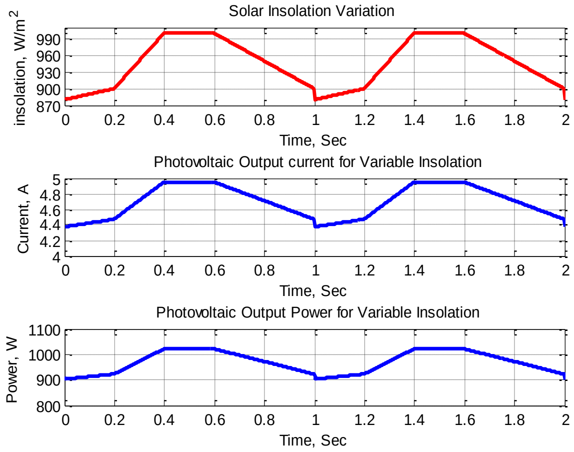

Fig. 8 simulation output which shows i) variation in solar insolation ii) PV output current for variable insolation and iii) PV output power for variable insolation.

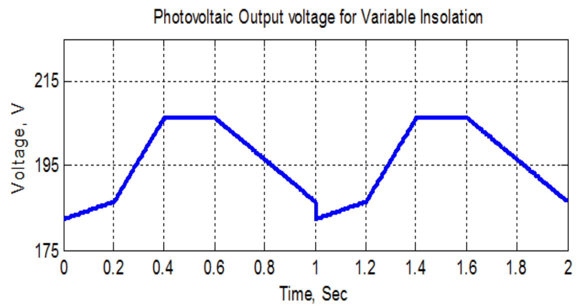

Fig. 9 PV output voltage for variable insulation

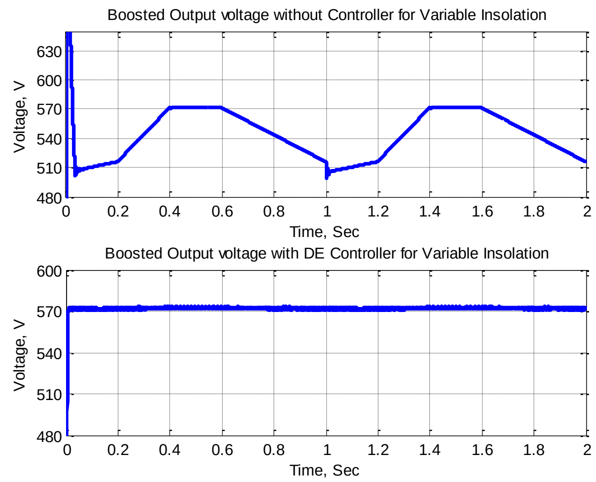

Fig.10 Output of boost converter without controller and with DEC for variable insolation.

The following five cases were taken into consideration:

Base Case : Load flow without PV

Case 1 : Load Flow with variable insolation PV & without DEC

Case 2 : Load Flow with constant insolation PV of 1000 W/m^2 & without DEC

Case 3 : Load Flow with constant insolation PV & with DEC

Case 4 : Load Flow with variable insolation PV & with DEC

After doing the analysis, comparisons were made with the difference in percentage of rise in voltage taken on an average basis between base case i.e., load flow without PV and cases 1-4. Bus no 4, 18 and 33 are randomly chosen for the analysis and the results are shown in Table II

TABLE II. Load Flow Result of IEEE 33 Bus Distribution System

	Base case	Case 1	Case 2	Case 3	Case 4
p.u voltage (at bus 4)	0.9668	0.9822	0.9863	0.9916	0.9919
Voltage improvement (in %)	0	1.54	1.95	2.48	2.51
p.u voltage (at bus 18)	0.8820	0.8987	0.9031	0.9089	0.9091
Voltage improvement (in %)	0	1.67	2.11	2.69	2.71
p.u voltage (at bus 33)	0.8867	0.9037	0.9082	0.9141	0.9143
Voltage improvement (in %)	0	1.7	2.15	2.74	2.77
Average Voltage improvement in all buses (in %)	0	1.552	1.966	2.506	2.531

It is found that minimum voltage occurs at bus 18 for all the four cases but the voltage is improved by 0.0271 p.u in case 4 which is 2.71% when compared with the base case. Further the voltage in bus 18 for case 4 is improved by 0.0104 p.u when compared with integration of PV without controller (case 1). Moreover the average difference in voltage in percentage is more in case 4 which shows that voltage profile in all buses could be improved by an average of 2.531. It can also be seen that the PV system which uses DEC for boost converter has the strongest voltage support capability in node no 33 which is 2.7642 percentage from case 1.

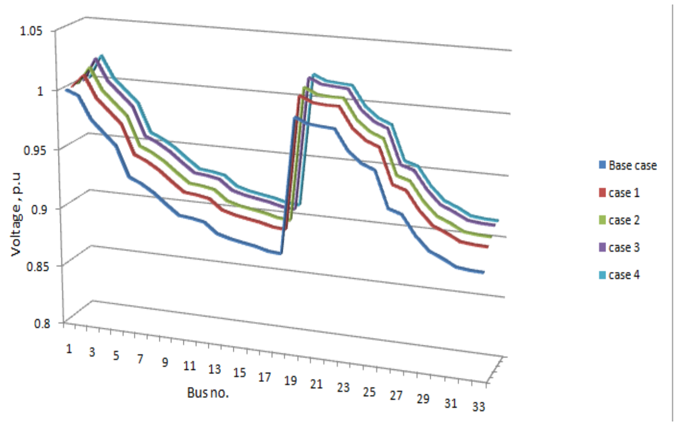

Fig. 11 Load flow output of PV at bus 2 (base case and cases 1-4)

It is also found that comparatively more amount of voltage is increased in buses 33. One thing to be noted is that the bus 33 and 18 are terminal buses. These results have confirmed the effectiveness of the proposed controller which tracks the change in input as well as output voltage and adjusts the duty cycle of the boost converter.

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accordingly which reaches and stabilizes at the reference. value in a very short duration and thus helps in improving the voltage profile considerably. This method is more advantageous to improve the voltage at the terminal node in radial distribution system.

It is seen that the system voltage has improved at all the buses by the injection of PV at bus 2. The percentage rise in each bus is given in Fig. 11.

V. CONCLUSION

In this paper, a new control scheme in photovoltaic system which provides constant dc voltage is constituted. The variation in output DC voltage of the converter with variable insolation of PV system with DEC used to control boost converter and the corresponding change in duty cycle is studied with a PV array consisting of two modules. It is found that there is an inverse relationship between insolation variation and duty cycle. However, the output voltage of the converter is maintained constant. The same circuit when tested with change in load also shows that the output voltage is constant. [ref]. The effect of variable insolation of PV array with DEC controller and the change in duty cycle and output dc voltage and the corresponding change in grid voltage is studied on IEEE 33 bus distribution system for a PV array consisting of 2 modules in series with a insolation variation from 880 to 1000W/m^2. From the result obtained it can be demonstrated that this method is capable of maintaining the load voltage regulation while feeding available power from the PV source and results in improved voltage profile. The obtained result proves that the proposed method is reliable and has good voltage profile improvement. Hence it could be concluded that addition of PV provides more voltage support to the terminal nodes and hence increases the reliability of the entire network.

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